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Judging Distance from Ocular Convergence

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Subjects misjudge distances considerably when forced to rely on extra-retinal information. Nevertheless, they can reproducibly set a target to the same distance as a reference, or to double or half that distance, even when they have to look back and forth between them because they are prevented from seeing one when looking at the other. Our explanation for this apparent discrepancy is that people have access to reasonably accurate extra-retinal information on *changes* in ocular convergence, but can only use this information to judge distances if they had reliable information about the orientation of the eyes before the convergence changed.

Spatial vision Vergence Distance Eye movements Human

INTRODUCTION

Differences between the views of a scene from two slightly different vantage points provide a rich potential source of information about distances. By combining the directions from two vantage points, one could determine exactly where everything is. However, as we tend to direct our eyes at objects of interest, the required directions do not correspond with specific retinal locations. For instance, the image of the object we are looking at is always on the fovea, irrespective of its position in space. In order to know where the object is, the orientation of the eyes has to be taken into account.

There are a number of potential sources of information about the orientation of the eyes. The most obvious is direct extra-retinal information about ocular convergence (from motor efference or sensory feedback). However, extra-retinal information about ocular convergence—and the related state of accommodation—is reputed to be very poor (Collewijn & Erkelens, 1990; Gogel, 1961). Most subjects appear to be able to make some use of such information, but there is little consistency between subjects (Gogel, 1977; Morrison & Whiteside, 1984; Richards & Miller, 1969; von Hofsten, 1976), other than a systematic tendency to underestimate the range of target distances (Foley, 1980; Gogel & Tietz, 1973; Johnston, 1991). The tendency to see all isolated targets at about the same distance, irrespective of the convergence of the eyes, probably explains why the variability in the perceived distance of such targets was found to be surprisingly small (less than 5 min of arc in some conditions; Foley, 1980), whereas the variability in attempts to reproduce a distance with such targets is quite large (1–2 deg; Richards & Miller, 1969). If so, the latter provides a better indication of the variability in extra-retinal information about ocular convergence.

The alternative to using extra-retinal information would appear to consist of relying on retinal estimates of ocular orientation. Such estimates could, for instance, be based on vertical size differences (for details see Howard & Rogers, 1995) or the retinal location of the outline of one's nose. Rather than determining the orientation of the eyes, our visual system could also opt for measures that are insensitive to changes in the orientation of the eyes. This is so for relative disparities. Although interpreting relative disparities in terms of distances between the structures involved also requires a measure of the viewing distance [Foley, 1980; Johnston, 1991; van Damme & Brenner, 1997; Fig. 1(A)], this is no longer related to the orientation of the eyes, but could be any known distance. If any object's distance is known, all other distances could be derived from the relative disparities with respect to this object. Taking this approach one step further, our visual system could determine the viewing distance by combining disparities with other depth cues—such as texture or motion parallax—that scale differently with the viewing distance (see Johnston, Cumming, & Parker, 1993; Johnston, Cumming, & Landy, 1994; Frisby, Buckley, Wishart, Porrill, Gårding, & Mayhew, 1995). The actual viewing distance could be recognised by its being the only one for which the cues provide consistent information.

Although retinal measures certainly contribute to our judgements of distance, Enright (1991) has recently shown that subjects can perform at least one task without them. In his experiments none of the above-mentioned retinal mechanisms could be involved because he used small isolated targets in the dark. He found that subjects were able to reproduce a distance to within approx. 3 min of arc (standard deviation of target vergence; target vergence being the vergence angle that would be required

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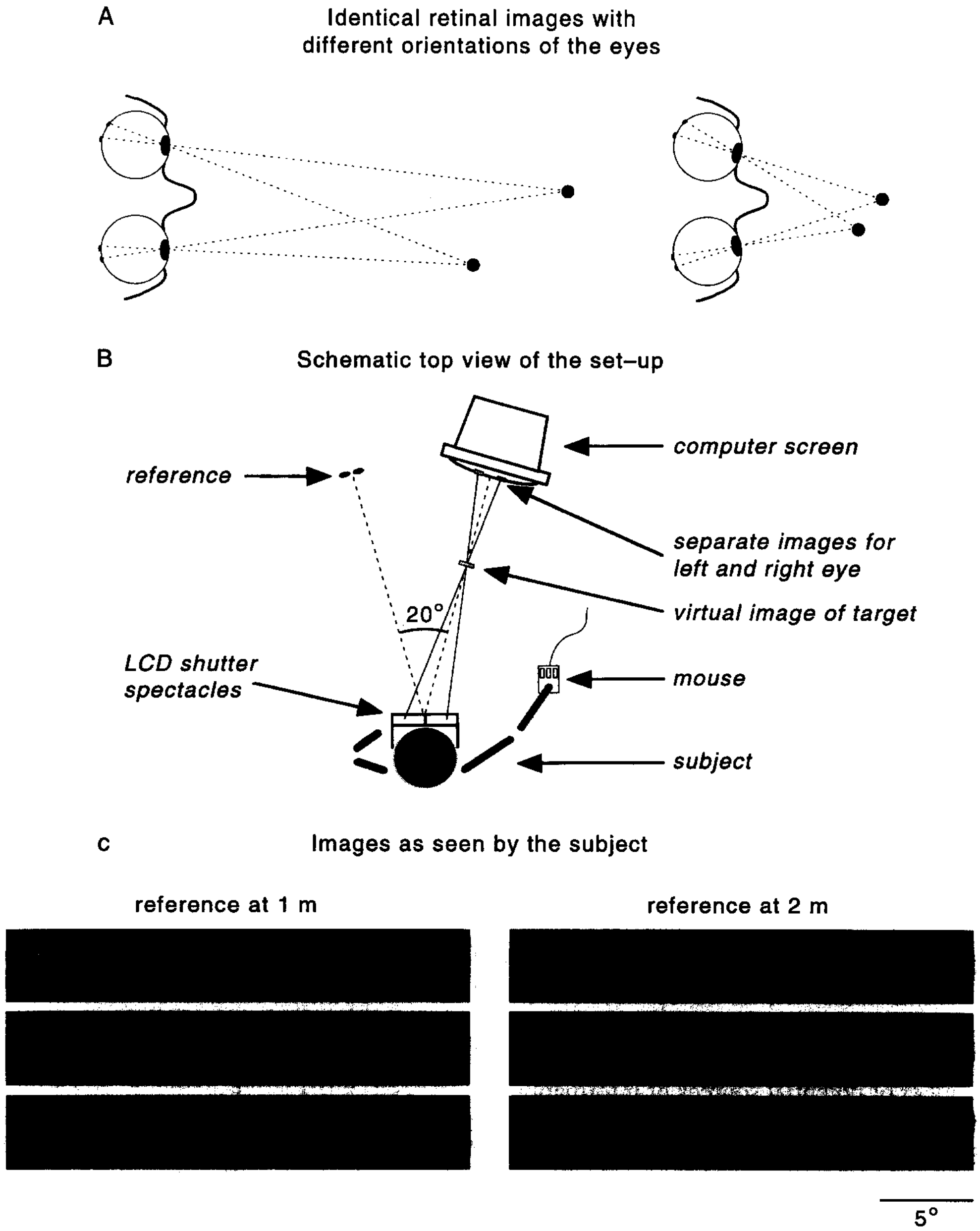

FIGURE 1. (A) Schematic illustration of why relative disparities cannot specify objects' distances—neither relative to each other or from the observer—even considering their retinal positions. The same applies for extra-retinal information about the change in the orientation of the eyes (i.e., how much each eye is rotated) as the gaze is shifted between the two targets. If the distance of either of the targets is known, however, such information is enough to specify the distance of the other. (B) Our experimental set-up. The subject's eye movements were recorded and his direction of gaze was used to determine which stimulus was visible. (C) When the subject looked to the left, only the reference was visible. When he looked to the right, only the adjustable target was visible. During saccades between the two neither was visible.

to fixate the targets) even when they had to look back and forth between the targets to do so (the two targets were placed so that whenever one was fixated, the other "disappeared" into the blind spot of one eye; Wright, 1951).

Enright suggested that subjects were comparing retinal disparities before and after an isovergent saccade. He emphasised that subjects need not know the orientation of their eyes or the actual distance of the target, and showed that ocular convergence could be maintained accurately enough across saccades for this mechanism to work. The only extra-retinal information that is required is the identification of saccades during which vergence was not expected to change, which would involve a very limited form of motor efference.

In everyday life, objects of interest are not always at the same distance. Ocular convergence changes during the saccades that shift our gaze between such objects (Collewijn, Erkelens, & Steinman, 1995; Enright, 1984). For large differences in distance, convergence must change to ensure fusion. In the present study we examine the extent to which performance deteriorates when saccades are not isovergent. We do so by asking subjects to make half and double distance settings under conditions that force them to look back and forth between the target and a reference. In particular, we explore the possibility that subjects have reliable extra-retinal information about the change in convergence when shifting their gaze, but have to know the distance of one of the fixated structures for this to translate into a change in viewing distance [in the same way as described for relative disparities above and in Fig. 1(A)]. This would explain why subjects were found to judge the distance of isolated targets more consistently when they were allowed to look around in an illuminated room between trials (von Hofsten, 1976).

MATERIALS AND METHODS

Our reference consisted of four red light-emitting diodes arranged to form a 2 cm square. The adjustable target consisted of two dim red 5 mm squares on a computer screen (38.7 × 29 cm; 1280 × 492 pixels; 120 Hz; spatial resolution further refined with anti-aliasing techniques). LCD shutter spectacles ensured that one square was seen by each eye (red stimuli were used, and additional red filters were attached to the spectacles, because the shutters only work well enough for long wavelengths of light). The reference was approx. 20 deg to the left of the adjustable target [Fig. 1(B)]. The angular dimensions of a pixel, of the light-emitting diodes and of the adjustable target were approx. 1, 14 and 17 min of arc when the reference and computer screen were at a distance of 1 m, and approx. 0.5, 7 and 9 min of arc when they were 2 m away [Fig. 1(C)].

During the experiment, the adjustable target and the reference were never visible at the same time. Whether the light-emitting diodes (reference) or the image on the monitor (target) was visible depended on the subject's horizontal eye movements (EOG recordings). Neither target nor reference was visible from the moment a saccade was detected (velocity threshold based on calibration trials before the experiment) until the eyes slowed down again. After that, the reference was turned on if the saccade was to the left, and the target was turned on if the saccade was to the right. This procedure ensured that subjects never saw the two stimuli simultaneously. As the shift between the targets was driven by eye movements, we can also be certain that subjects never saw the targets consecutively during a single fixation. Moreover, our procedure ensured that the target that was not fixated was never visible. As a consequence of the stimuli only appearing at the end of the saccade—which was necessary in order to be certain that subjects could not use the disparities before the saccades as a measure of the change during the saccade—there was no visual input to guide the saccades, so that subjects had to make saccades to remembered positions.

Subjects could change the simulated distance of the adjustable target by moving the computer mouse. The range of possible distances was between 20 cm and 100 m. The initial value on each trial was chosen at random from within this range. The relationship between a given movement of the mouse and the resulting change in vergence angle was linear, and differed by up to a factor of 6 between trials. Subjects were free to take as long as they liked to make their settings. They indicated that they were content by pressing a button.

The only things that were ever visible during the experiment were the targets and the written instructions (on the screen) that separated blocks of trials. Altogether, there were six tasks. The first was to set the adjustable target to the same distance as the reference, as in Enright's experiments. The second was to set the adjustable target to the same distance as in the first task in the absence of the reference. For this task only the adjustable target was visible, irrespective of the subject's eye movements. Subjects knew in advance that they would be expected to try to set the adjustable target to the same distance as they had set it during the preceding task, so that they could try to remember this distance. It was also evident to them that the absent reference was now completely irrelevant. The third task was to set the adjustable target to half the distance of the reference. The fourth was to set the adjustable target to the same half distance without the reference. This task was identical to the second task, except that the distance that was to be reproduced was different. The fifth was to set the adjustable target to twice the distance of the reference. The sixth was to set the adjustable target to the same double distance without the reference. The tasks were performed sequentially in blocks of 10 trials each. Three subjects (including the authors) first performed this sequence at a viewing distance of 2 m, and then again at a viewing distance of 1 m.

The difference between the vergence required to fixate a target and the vergence required to fixate a second target at half the distance depends on the distance of the initial target. Unless the stimuli are extremely close, the change in vergence when shifting one's gaze to half the distance is approximately equal to the initial vergence angle. Thus, in our half distance task, any variability in the judged distance of the reference (when expressed as an angle of convergence) will lead to an equivalent variability in the set difference in target vergence. To obtain correct settings the reference must therefore be judged to be at the correct distance. For the reference to reduce the variability it is enough that it be judged to remain at the same distance across trials.

We chose the square configuration of the reference in the hope that the "familiar" size of the square would help maintain its perceived distance. Moreover, the naïve subject was also shown the set-up in advance to ensure that he was aware of the distance of the reference. In a pilot study (with self-paced rather than eye-movement triggered switching between target and reference) naïve subjects who had no prior notion of the distance of the reference (a single light-emitting diode) made large systematic errors when asked to make half distance settings. The set differences in convergence were approximately appropriate for the distance at which they perceived the reference (according to their verbal reports). We decided to help the subjects to judge the distance of the reference as correctly as possible in the present experiment in order to minimize the conflict with accommodation.

We used the relatively small distances of 1 and 2 m (despite reports that the standard deviation in both manually indicated target distance, and in half distance settings decrease with distance; Foley & Held, 1972; Foley, 1967) to ensure that the retinal disparities after an isovergent saccade would be too large to be of any use when making the settings. Moreover, we examined whether one of our subjects made isovergent saccades when making half and double distance settings by having him repeat the settings with the reference at 1 m, while we recorded his eye movements with the scleral induction coil method (Collewijn, Van der Mark, & Jansen, 1975). In this case we were able to use a position (version angle) threshold to determine which stimulus was visible. The orientations of the eyes and the presence or absence of the stimuli were determined at a rate of 1000 Hz.

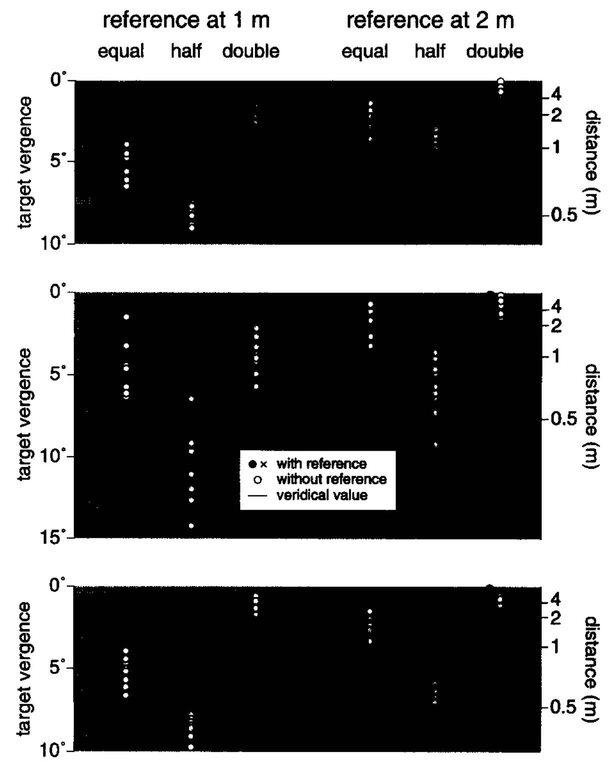

FIGURE 2. The three subjects' equal, half and double distance settings when the reference was at 1 and 2 m. Solid symbols and crosses: settings when either the target or the reference was visible, depending on which the subject was looking at. The crosses are for the settings that were made while the subject's eye movements were recorded with scleral coils. Open symbols: settings when only the target was visible (the task was to replicate the former settings without the reference). The lines indicate perfect performance. Distances are given both as target vergence (the vergence required to fixate the target considering the individual subject's inter-ocular distance) and in meters.

RESULTS

Figure 2 shows the set target distances and corresponding target vergences for each subject in each task and for each distance of the reference (10 trials each). When subjects looked back and forth between target and reference (solid symbols), the settings were close to veridical (horizontal lines). When they attempted to replicate the distance without the reference (open symbols), the settings were clearly more variable. WvD's settings were slightly less accurate while his eye movements were recorded with scleral coils (crosses).

Figure 3 shows the average standard deviation for each task. The much higher variability in the absence of a reference was accompanied by an impression of regularly losing any sense of distance. Figure 4 shows two representative saccades from the third half-distance setting (A) and gaze plots of the ninth half- (B) and double- (C) distance settings. Dots are drawn in grey whenever both targets were off. It is evident that the subject did not make isovergent saccades. In fact, the average change in vergence during the last six saccades of each trial was highly correlated with the subject's settings ($R^2 = 0.99$), and was approx. 70% of the change in vergence that would shift his gaze between the two targets.

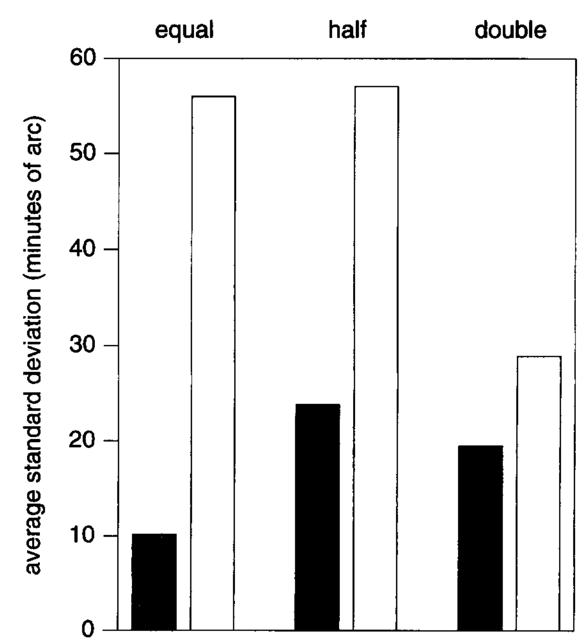

FIGURE 3. Average standard deviations within blocks of 10 trials for each task (equal, half and double distance settings) averaged across subjects and reference distances. Shaded columns show the variability when the reference was present. White columns show corresponding data when it was not.

DISCUSSION

As the task was the same for all unreferenced settings (replicating a previously seen distance) we had expected identical results for this task at all distances. The conspicuously small variability in the unreferenced double 2 m settings (see Fig. 2) suggests that subjects were probably using the furthest distance that could be set as a reference. Thus, the reliability of extra-retinal information about the orientation of our eyes is probably overestimated in at least part of our unreferenced data. If accommodation had played an important role in our experiments, subjects would have performed the unrefer-

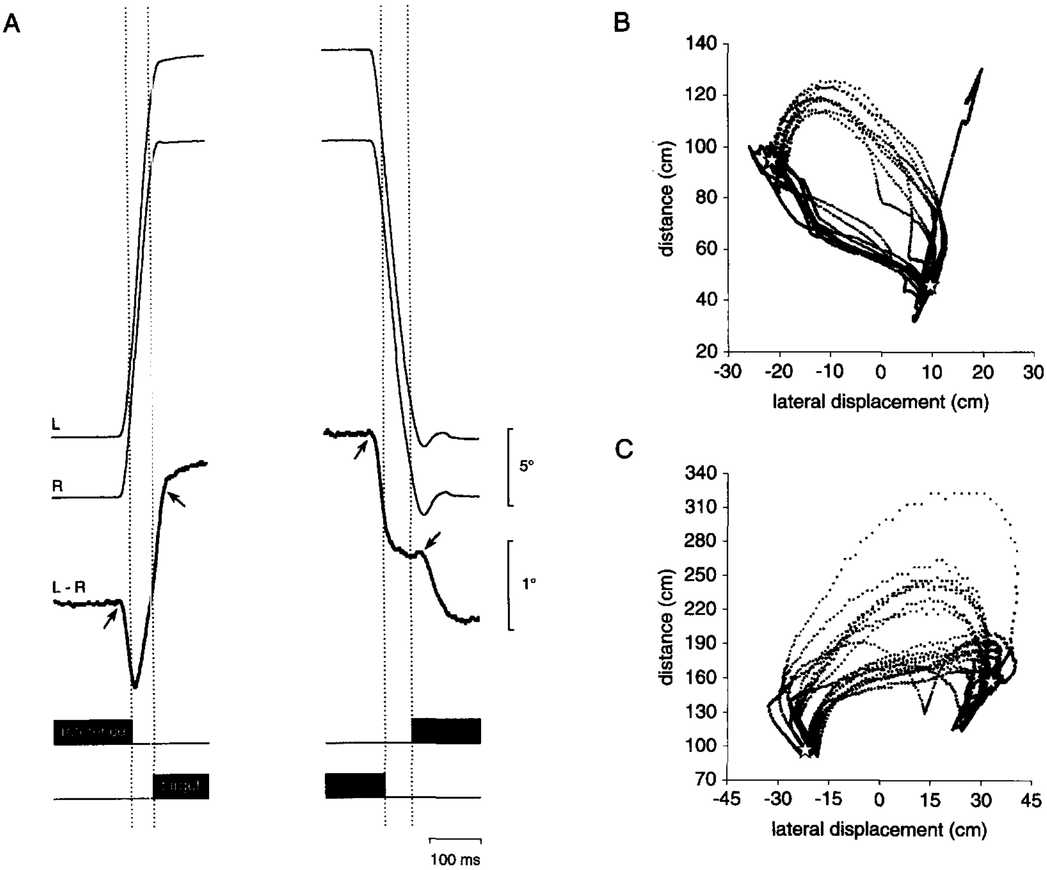

FIGURE 4. Examples of eye movements. (A) Two consecutive saccades from WvD's third half distance setting. The vertical lines show the interval between reference offset and target onset; and vice versa. The arrows on the vergence trace (L–R) indicate the beginning and the end of the saccade. (B) Complete gaze plot of the ninth half distance setting. Each dot represents the position the subject was looking at (in the horizontal plane), as determined from the orientations of the eyes (1000 Hz). The dots have been drawn in grey when both targets were off. The stars indicate the position of the reference and the set (simulated) position of the target. (C) Similar gaze plot of the ninth double distance setting. It is evident that WvD did not make isovergent saccades. Note the systematic difference between eye movements towards the target, and ones towards the reference.

enced task best for the equal distance settings, because the computer screen was at the same distance as the reference. There was no indication of this (see Fig. 3).

Our results for equal distance settings are similar to those of previous studies, in which it was ensured that subjects made sequential judgements by using blind-spot spacing (Wright, 1951; Enright, 1991), intermittent presentation (Enright, 1991) and fine texture that is invisible when viewed peripherally (Enright, 1996). The standard deviations in our study are approximately twice as large as Enright's (1991) values. Considering the numerous differences between the studies, and the large differences between subjects, we consider our findings to be consistent with Enright's.

The standard deviations in our half and double distance settings are approximately twice as large as Foley's (1970) values, which is likewise a modest difference, considering the issues discussed above and the fact that Foley took no precautions to ensure that subjects were doing sequential judgements because he was dealing with quite a different issue.

The most important finding is that subjects performed only slightly worse in the half and double distance tasks, than in the equal distance task. That the variability was larger for the half and double than for the equal distance task is not surprising, because judging how far half or twice the distance is could introduce an additional source of error. In addition, slight variations in the judged distance of the reference will increase the variability in the half and double distance settings, but will not influence the equal distance settings. Considering these additional sources of variability, we conclude that the accuracy of extra-retinal information for no change in ocular convergence is not fundamentally different from that for other magnitudes of convergence.

Our study cannot tell us whether the actual shift in gaze has to be precise, or whether absolute retinal disparities are also considered. It could be that the subjects compared extra-retinal information about the orientation of their eyes when fixating the two targets. This would require that they shift their gaze between the targets, but not necessarily that they do so with a single saccade. It implies that they have a continuous sense of the orientation of their eyes, although this sense may be incorrectly "calibrated". Alternatively, the subjects may have detected errors in fixation after making precisely planned gaze shifts (i.e., ones of which the magnitude is assumed to be known in advance). We measured the ocular convergence that took place during one subject's saccades, and found that it only changed by about 70% of the amount that would be required to shift his gaze from the reference to the position he set on that trial. Although this may appear to contradict this proposal for the use of motor efference information, the change in vergence clearly continued after the saccade. As it is impossible to determine—on the basis of our data—whether a continuation of the change in vergence that took place after the saccade was part of a planned shift in gaze, or the correction of an error, this alternative cannot be dismissed. Finally, the subjects may have combined extra-retinal information on changes in the orientation of the eyes with the difference in absolute retinal disparity before and after the gaze shift. What all these mechanisms have in common is that they all rely on extra-retinal information about changes in ocular convergence.

It may seem strange that we should have reliable information about changes in ocular convergence, because—as already mentioned—such information can be of little use for judging distances if we do not know the orientation of the eyes before the change (1 deg of ocular convergence could be due to a shift in gaze from 20 to just over 21 cm or from 2 to approx. 4 m). However, if one knows the orientation of one's eyes before a saccade, then knowing the change provides information about the new orientation. The reported unreliable judgements of distance when forced to rely on ocular convergence are obviously based on studies using limited visual environments (as in this study), in which one would have to keep track of the orientation of the eyes by integrating across many changes in convergence. In everyday life, we may usually have enough visual information from which to judge the orientation of our eyes, both directly (e.g. from vertical disparities; Rogers & Bradshaw, 1993; Howard & Rogers, 1995) and indirectly (on the basis of visual information about the distance of the object we are looking at; for overviews of possible cues see Cutting & Vishton, 1995; Gillam, 1995; Sedgwick, 1986). If so, the use of extra-retinal information about changes in ocular convergence may only be required when there is not enough retinal information during a certain fixation, for instance when fixating a relatively isolated object such as a bird in the sky. The accuracy of judgements under such conditions will depend both on how well we can judge the change in vergence since the previous fixation, and on the accuracy of our knowledge of the orientation of the eyes before the change.

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